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"ISOTROPIC" COVERAGE ON SATELLITES OF LARGE DIAMETER AS COMPARED WITH WAVELENGTH

N. E. Feldman

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N. E. Feldman 40p 19 refs

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PREFACE

This Memorandum describes techniques for wide angle coverage for use on satellites whose diameter D is large compared with wavelength λ. The study is part of RAND's continuing investigation for NASA of communication satellite technology, but has application to space communications in general--satellite tracking, telemetry, command links--at microwave frequencies.

SUMMARY

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Although satellite antennas of a few db gain are already in use, and large high gain antennas will become standard as accurate, reliable stabilization techniques are evolved, broad angle coverage antennas will still be advantageous for selected missions. This Memorandum describes techniques for achieving such broad angle coverage.

The first method involves extending an antenna on a long mast. A biconical antenna is used which provides omnidirectional coverage (360 deg in azimuth) above -1 relative to isotropic, over 90 per cent or more of the surrounding space.

The second method uses two extended balanced logarithmic conical spiral antenna elements, diametrically opposite and circularly polarized in the opposite sense as seen by an observer in the far field to provide "isotropic" (constant power over a sphere although of variable polarization) coverage. An individual element provides circular polarization over a hemisphere. Coverage over 100 per cent of the surrounding space appears achievable with a gain of -3 db relative to isotropic.

The third method uses frequency diversity techniques. A number of alternatives are described providing either 100 per cent coverage, or coverage in the direction of the ground receiving terminal by selecting one of two halfwave antennas. Compared on the same basis as the two previous techniques, the resultant gains vary from about -2 db to -6 db depending on the complexity of the satellite and ground terminal equipment and the operating procedure.

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I. INTRODUCTION

Numerous recent publications on communication satellites have mentioned high gain satellite antennas for satellite-to-earth links.[1-4] A trend toward greater satellite antenna directivity is evident; antennas whose beam width subtends the earth[1] are expected to give way to antennas whose beam width covers a particular region.[2-4] Systems utilizing numbers of narrow beams pointed in different directions[2,3] have been proposed. Behind all these schemes lies the valid assumption that as stabilization systems demonstrate acceptable orbital reliabilities and improved accuracies, higher gain antennas will be used.[4] There are, however, penalties and limitations associated with the use of directive antennas; the limitations assure a continuing utility for antennas providing wide angle coverage. Stabilized systems complicate the initial orbital conditions which must be met, and may reduce the useful satellite lifetime.

Two situations, for example, in which broad angle coverage antennas will continue to be desirable are:

1. During a flight phase before stabilization in which the aspect to ground is variable and contact must be maintained, e.g., the transfer ellipse of Syncom I.
2. To maintain communications where other factors dictate an unstabilized satellite, or where other factors, e.g., solar cell orientation or the requirements of an experiment dictate an unfavorable attitude of the spin axis. For elliptical orbits, trading antenna gain for greater beam width sacrifices information rate at apogee for higher utilization of the

satellite over the orbit. This is particularly of interest for the 63 deg inclined elliptical orbit.

The transition to larger satellites, and to higher frequencies for telemetry (.960 Gc and 2.3 Gc) and communications (4 Gc and 6 Gc) eliminates the standard solution for roughly isotropic coverage--the turnstile* antenna integral with the body of the satellite. This Memorandum will discuss this limitation of the turnstile and then discuss techniques for obtaining broad patterns under the condition of large D/λ.

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*Two crossed halfwave antennas energized by currents of equal magnitude but in phase quadrature.

II. A LIMITATION IMPOSED BY THE USE OF THE TURNSTILE FOR "ISOTROPIC" COVERAGE

For satellites having diameters of about $\lambda/2$ or less, the turnstile antenna can be used to provide coverage over 4π steradians. Even at the lower end of the lower common carrier band proposed for satellite communications, however, the turnstile imposes a severe power restriction if solar cells are used. The total spherical surface area at 3.7 Gc for $D = \lambda/2$ is 52 cm^2. If this were covered entirely with overlapped 1 x 2 cm solar cells capable of generating 25 mw each when fully illuminated in space, only 180 mw would be generated, since the equivalent of only one-fourth of the area is illuminated at any one time. Assuming that half of this power is deliverable to the equipment during its life, and that 15 per cent of this power is converted to microwave power by solid state devices, the resultant 13 mw output is insufficient to permit small ground terminals to handle a single voice channel, even in low (1000 n mi) altitude orbits. At 2 gc, however, the larger diameter and higher microwave conversion efficiency may make 50 mw available. In this case, a 30-ft diameter receiving antenna would permit one voice channel for 1000 n mi orbits, for the conditions given in Table 1. Such a system would function but would be disadvantageous because of the need for many short hops via relay stations, and because it would have too small a capacity--a single, one-way voice channel--per each 30-ft receiving antenna.

Table 1

PARAMETERS FOR A SATELLITE-TO-GROUND LINK FOR A $D = \frac{\lambda}{2}$ SATELLITE

Frequency	2 Gc
Saturated output power, P	50 milliwatts
Minimum satellite antenna gain, Turnstile	-1 db
Orbital altitude	1000 n mi
Receiving antenna diameter	30 ft
Ground antenna efficiency	50 per cent
System noise temperature, NT_s	180 deg K
Microwave, tracking, oxygen, and water vapor losses	2 db
Frequency modulation index, m	10
Feedback factor, $10 \log_{10} F^2$	20 db
C/N in the IF (4b) for one 4 kc channel allows for a 6 db margin above RC filter threshold	17 db
Output S/N, $3m^2 \left(\frac{C}{N}\right)_{2b}$ for test tone	45 db
Average S/N for average talker	30 db

An alternate source of power for such space missions is the isotope power source. For missions requiring a design life of three to ten years, isotopic power systems range in performance from 0.5 to 2 mw/cm^3. Allowing one half the satellite volume for the power source, the available power is somewhat less than was obtained from the solar cells.

Thus on the basis of the severe power limitation, antenna systems such as the turnstile, which restrict satellite diameters to about $\lambda/2$, are of limited utility at S band and above. A factor of two increase in the allowable satellite diameter would not alter this conclusion. Thus where wide angle coverage is necessary, other techniques must be used.

III. A BROAD BICONICAL PATTERN

On Telstar, a large number of radiating ports uniformly spaced around the equator of the satellite produce an omnidirectional pattern (360 deg in azimuth) with one null 10 db below isotropic at 67 deg off axis. On Relay, which has an antenna on a 27 in. mast, the gain is 10 db below isotropic at about ± 57 deg. Since broad angle coverage has increased utility when it corresponds to a gain as close as possible to isotropic, the broadest beamwidth obtainable between points 1 db down from isotropic ($2\theta_m$) has been selected as a criterion for comparing omnidirectional patterns. On this basis, neither the Telstar nor Relay antenna has a θ_m exceeding 35 deg. It will be shown that broad patterns having a -1 db beamwidth exceeding the -10 db beamwidth of Telstar and Relay are achievable for additional complexity.

One possible antenna for providing broad patterns is the biconical antenna. The results of analytical as well as experimental studies of conical antennas providing patterns of the type of interest here were reported in the literature years ago.

Reference 5 examines radiation from spherically capped wide-angle conical antennas fed by a coaxial line. For a conical flare angle α of 60 deg (Fig. 1), it calculates E field patterns as a function of ka, i.e., 2π times the cone radial length in free-space wavelengths, for $1 \leq ka \leq 8$. Reference 6 contains measurements on conical patterns that compare closely with the theoretical patterns of Ref. 5. Unfortunately, the Ref. 6 measurements were limited to a cone height $A \leq 270$ deg, i.e., $ka \leq 4.7$.

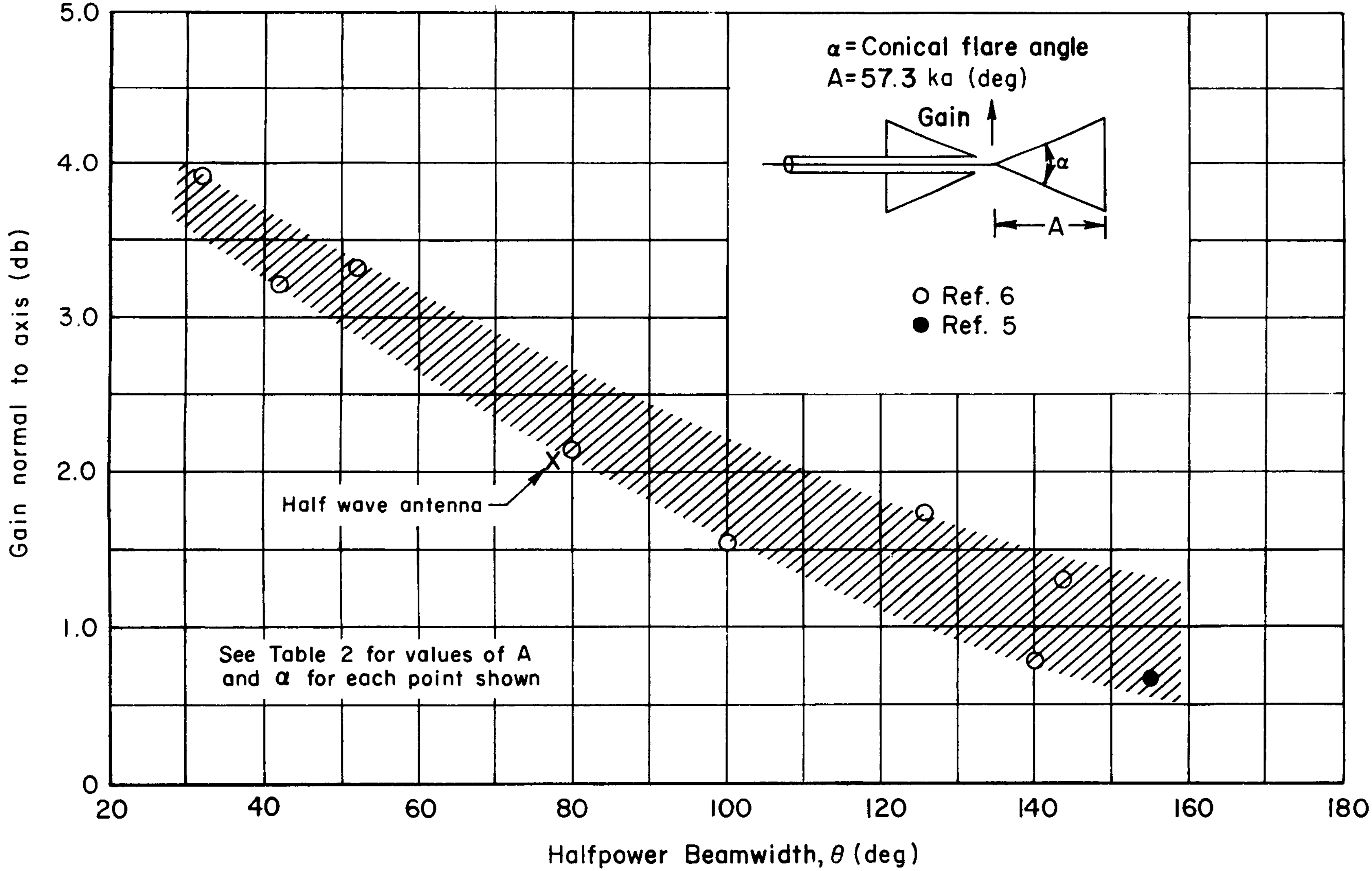


Fig. 1 — Gain of biconical antennas with broad patterns

Based on these experimental results, Fig. 1 shows the gain normal to the axis as a function of halfpower beamwidth Θ. Table 2 identifies the physical characteristics of the antennas selected[5,6] by means of A and α.

Table 2

BROAD BICONICAL PATTERN CHARACTERISTICS

Half-Power Beam Width	Gain Normal to Axis Relative to Isotropic	Approx. -1 db Half Beam Width	Gain Corresponding to Θ_m	Electrical Length of Cone	Flare Angle
Θ (deg)	$G(0^{\circ})$ (db)	Θ_m (deg)	$G(\Theta_m)$ (db)	A (deg)	α (deg)
32	3.9	24	-1	210	30
42	3.2	27	-1	210	40
52	3.3	30	-1	180	30
80	2.2	40	-1	60	50
100	1.5	46	-1	180	90
126	1.8	58	(-1.08)	240	60
140	.8	65	-1	255	50
144	1.4	71	(-1.16)	270	60
155	.7	77	(-1.26)	430	60

The -1 db beamwidths are plotted in Fig. 2.

Of the nine patterns examined, three dipped slightly below the -1 db level, giving values of θ_m which are low compared to the their large halfpower beamwidths, θ. In these three cases, the table shows in parentheses the corrected gain to which these angles correspond. From the References, it is evident that many combinations of A and α give the same beamwidths. Since the References treat only a few discrete values of A and α, it is quite possible that even larger values of -1 db beamwidth may be found.

Although a pre-extended biconical antenna on a mast is less desirable than a flush mounted antenna system producing an equivalent pattern, the pre-extended antenna is preferable to extension after the satellite is in orbit on the basis of reliability. As an example, however, of how the broad pattern biconical antenna might be implemented by extension in orbit, the length of the extension required will be estimated and one technique for achieving such extensions will be discussed briefly.

Since the biconical pattern has a null along the mast axis, the satellite body has a greater perturbing effect on the field than does the mast. Increasing the length of the mast not only reduces the solid angle shadowed by the satellite, but also reduces the intercepted and thus the reflected energy. The intercepted energy

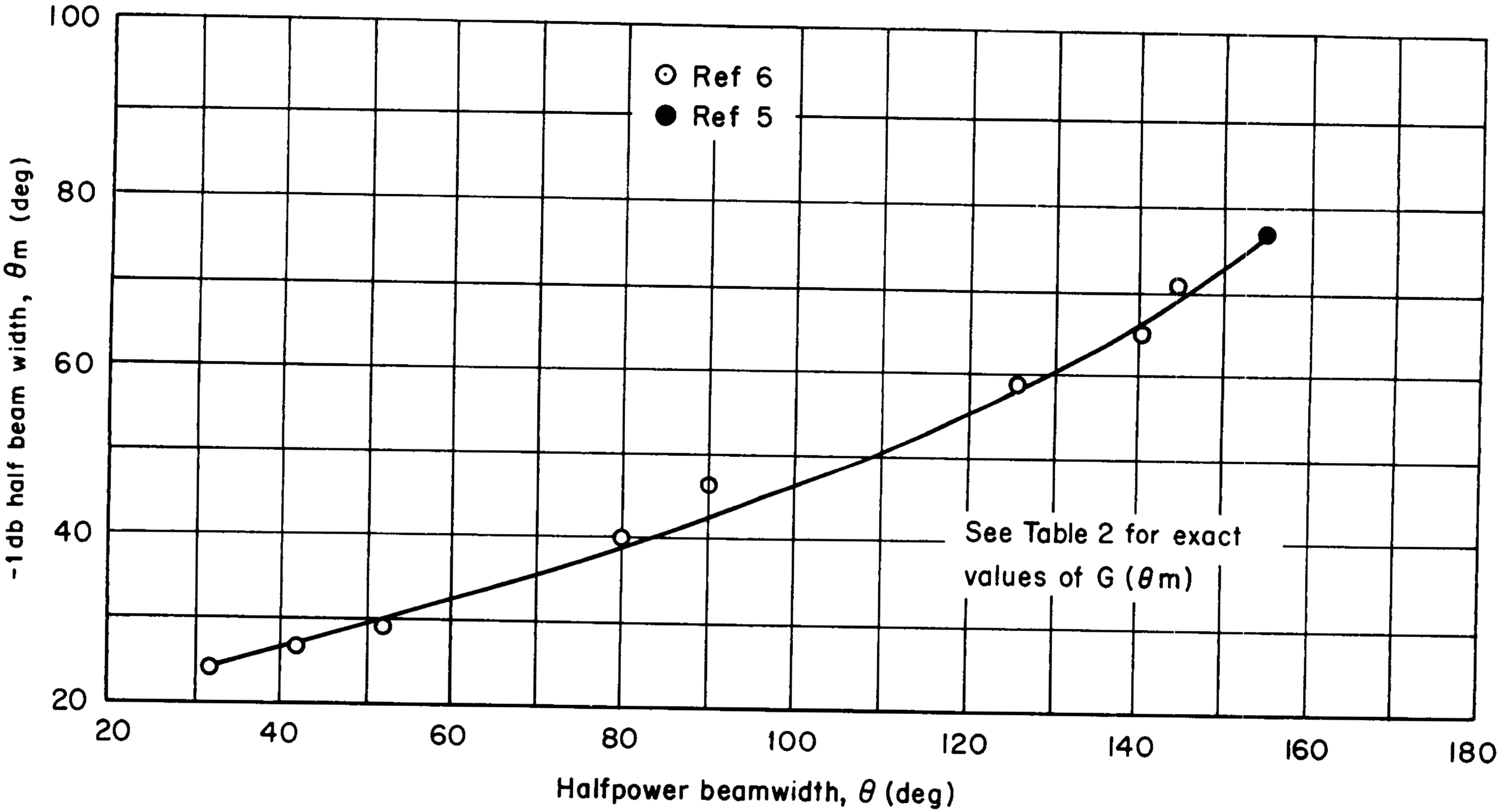


Fig. 2 —Halfangle between points 1 db below isotropic (θ_m) versus halfpower beamwidth

decreases because of the inverse square spreading loss, and because of the directivity of the antenna pattern as well.

On Relay, the short mast reduced the gain in the direction of the satellite to 12 db or more below isotropic, and the resultant ripple in the pattern was somewhat over ± 1 db. Thus if the broad -1 db biconical patterns are not to be degraded by 1 or 2 db, extensions appreciably greater than two ft appear to be required. For patterns having a -1 db half beamwidth of 65 deg, the field is down about 20 db at an angle of 85 deg off the normal to the axis. Figure 3 shows the height of the boom h as a function of satellite diameter for an angle of 85 deg. D_{max} corresponds to the estimated maximum diameter that could be packaged inside the present Agena B vehicle.

An estimate of the perturbation due to scattering generated by a uniformly illuminated area, e.g., a solar panel having a maximum effective aperture of 1 sq ft for a 45 deg angle of incidence at 4.2 Gc, and is about + 1/4 db*. Although this appears to allow for an unnecessarily large margin, bending of the mast due to thermal gradients, i.e., from the unidirectional insolation, will increase the reflected energy. Absorbtive coatings and shaping of the satellite surface nearest to the source, e.g., a long cone whose vertex lies on the mast, can reduce the power density

*This assumes that the effect of the satellite on antenna impedance is negligible so that the radiation resistance of the source is unaffected.

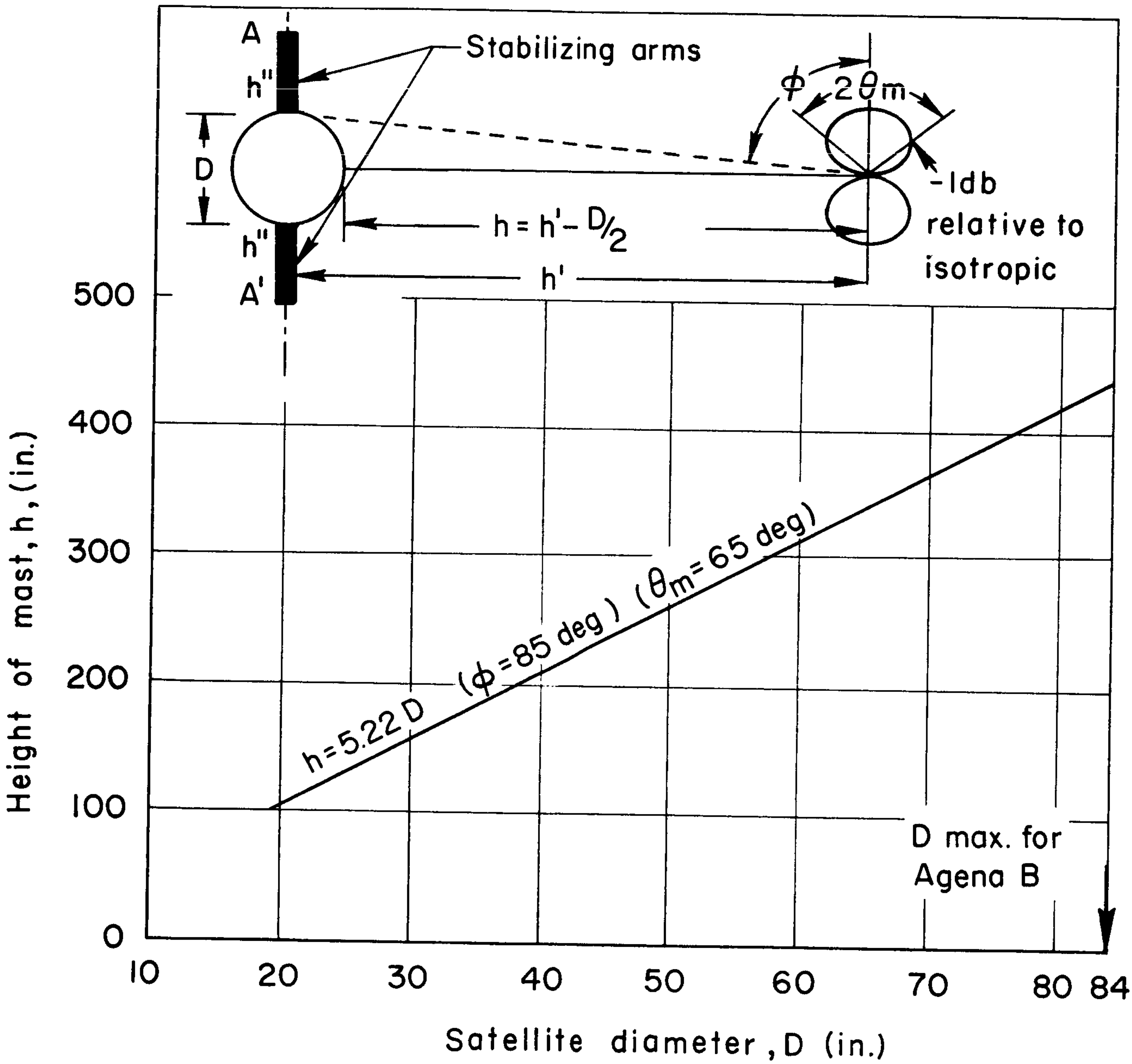


Fig. 3 —Height of mast required for broad biconical pattern as a function of satellite diameter

of the reflected signals and thus may permit a shorter mast.

For the same length mast, one may question whether the biconical antenna at the end of the mast cannot simply be replaced by a turnstile. Repeating the previous calculation indicates that in this case the satellite perturbs the field by 5 or 6 db, and thus produces an inferior pattern to those in use on Telstar and Relay. If, however, the satellite is built as a hemisphere with the mast projecting from the flat face, then the turnstile may offer excellent coverage for diameters of 60 in. or more. In this case, the primary pattern of the turnstile is significantly perturbed by only the main and first side lobes of the secondary pattern which lie within a few degrees of the axis of the mast.

Representative of a type of antenna erection device that appears to be adaptable to a coaxial line or circular wave guide is "STEM" (Storable Tubular Extendible Member), made by DeHavilland Aircraft of Canada, Limited.[7] STEM Type A-1 is a 75 ft extension .9 in. in diameter, which weighs 10 lb, including the drive motor. (Since this would be a one-shot operation, extension by controlled release of the strain energy stored in the coiled and flattened element is also offered by DeHavilland.) For roughly the same weight, a 2 in. diameter tube could be extended about 33 ft and a 10 cm circular wave-guide could be extended about 17 ft. The addition of a silver plating on the inside of the guide of about 2.8×10^{-4} cm to reduce loss, i.e., two skin depths at 2 Gc (to allow for wear during testing), would add less than 0.5 lb. Despite a 180 deg overlap of the tube edges, poor contact at the internal vertical seam may make it necessary to avoid modes that have circumferential currents. The TM_{01} mode does not have such currents and can be easily coupled to the TEM mode at the biconical antenna. Table 3 shows the attenuation of copper pipe for the TM_{01} mode. A center conductor inside the 2 in. diameter, 33 ft pipe would add 1 lb to the assembly, but the resultant coaxial line would have lower losses below 4 Gc if the ratio of outer to inner conductor diameters is roughly 3.6, the ratio for minimum loss, assuming negligible dielectric loss. To avoid the possibility of higher modes (i.e., non-transverse waves) propagating, as well as relatively high attenuations, the coaxial line is considered at frequencies where only the principal mode (TEM) exists.

Table 3

ATTENUATION OF COPPER PIPE AS A FUNCTION OF FREQUENCY
(db/meter)

Frequency	2-in. Pipe Diameter		10-cm Pipe Diameter		
(Gc)	TM_{01} [a]	TEM	TM_{01} [b]	TEM	TE_{11} [b]
1.0		.13		.07	
1.7		.18		.09	.1
2.3		.20	.1	.10	.0093
2.4		.21	.02	.11	.0085
3.0		.23	.01	.12	.0064
4.7	.1	.29	.009	.15	.005
5.0	.04	.30	.0092		.005
7.0	.023	.36	.011		.005
10.0	.025		.013		.0055

[a] From Ref. 8

[b] From Ref. 9

The use of telescoping circular waveguide, however, would permit the use of the TE_{11} mode, and above 3 Gc this would cut the loss roughly in half for a 5 cm radius circular waveguide, with much larger improvements below 3 Gc. One may thus conclude that extensible waveguide-fed antennas in the 2 to 10 Gc range appear feasible on a weight and loss basis.

Extension of a mast of length h makes the maximum moment of inertia axis parallel to axis A-A' (Fig. 3). For the communication satellite design discussed in Ref. 10, the moment normal to the spin axis with the mast extended may be as much as two and one-half times that about the spin axis, and rotation about the maximum moment of inertia axis will be induced. This will reduce the coverage, since the polar nulls will sweep out an increased solid angle. As a measure of the coverage effectiveness of the antenna, the per cent of surface area which lies 1 db or more below isotropic may be examined. In the case of undesired rotation about A-A', the fractional surface area swept out by the nulls is given by $\cos \theta_m$, and is large except for θ_m close to 90 deg, as shown in the upper curve of Fig. 4. In general such operation will provide an unacceptably large loss.

In order that the satellite not develop rotation about an undesired axis after being spun up about the axis of the mast, a necessary and sufficient criterion in the absence of external torques is that the moment of inertia about the spin axis be greater than the moment of inertia about any other axis. If side arms are extended of length h'' as shown in Fig. 3, the maximum moment of inertia axis can be made to coincide with the axis of the mast. For example, the appropriate length

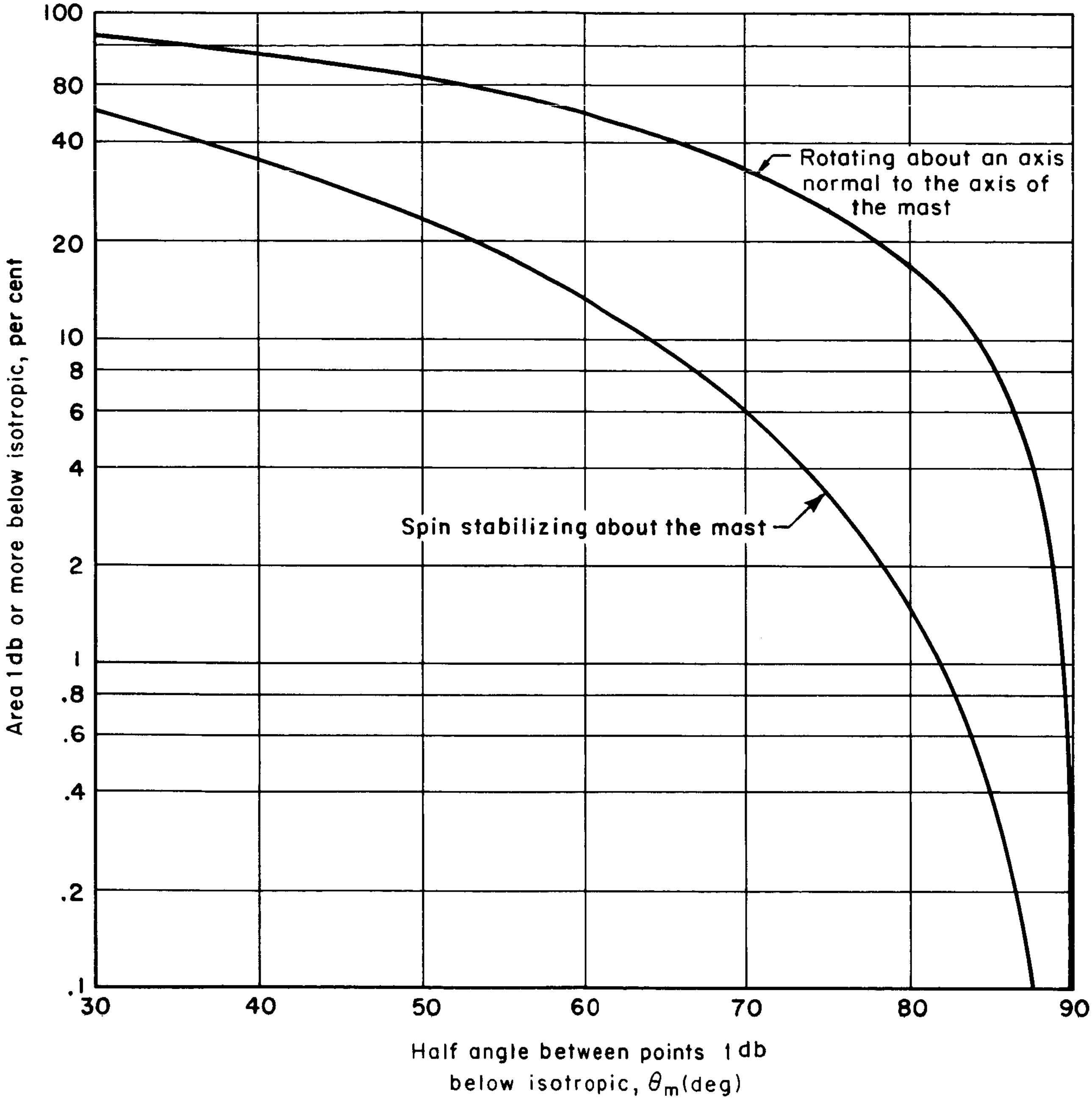


Fig. 4 — Per cent of surface area of unit sphere 1 db or more below isotropic

of the side arms, to make the ratio of the moment of inertia about the mast greater than that normal to the mast by 40 per cent for a particular communication satellite design,[10] varied from 70 per cent to 90 per cent of the mast height as the RF output power increased from 1 to 10 watts. For angular velocities of 100 rpm or more, the effects of all external torques upon the spin axis alignment are expected to be negligible. In all cases, it will be desirable to include a passive nutation damper to eliminate any error in alignment of the spin axis with respect to the antenna axis.

When the satellite is spin stabilized about an axis coinciding with the mast, the area more than 1 db below isotropic is not large for values of θ_m of 65 deg and more. The area of the two polar caps is given by $(1 - \sin \theta_m)$ and is plotted as the lower curve of Fig. 4. Less than 10 per cent area below -1 db is achievable, and values of 1 per cent or less may be feasible.

Although the rotating side arms do not move with respect to the antenna on the mast, they do move with respect to an antenna on the ground. Metallic arms, although of small diameter, could perturb the pattern in an undesirable fashion. Thus non-metallic arms may be preferable. The choice of material and its space deployment must be considered in terms of both the required electromagnetic effects and the space environment.

For simplicity, and because plastics are ideally suited to the STEM technique, the same method is proposed for deploying the stabilizing arms as was used for the antenna mast--a motor drive extension. Epoxy and styrene reinforced fibreglass appear to be suitable materials. In order to achieve roughly the same stiffness as the beryllium copper antenna mast, the thickness would have to be increased by a factor of five to ten. Since the density of the reinforced plastic is less (1 to 2 gr/cc versus 8.2 gr/cc), the weight per unit length would be about the same.

The dielectric constant of standard resins ranges from 2 to 5 from 10 cycles to 10 Gc and dissipation factors over this range of frequencies vary from about .0003 to 0.03. Because of these relatively low values and the thinness of the walls of the dielectric tube, i.e., 10 to 20 mils, it is not likely that the perturbing effect on the far zone field will be significant.

There are still the influences of environmental factors on the long term stability of the organic materials to be considered. Long-chain polymeric compounds degrade by breakdown in vacuum into volatile fragments, by charged particle radiation damage through ionization, and by surface destruction due to solar photon emission.[11] At the low side arm temperatures anticipated in this application, the weight loss should be negligible and the photon surface damage should be immaterial. Damage to engineering properties by ionization may be significantly reduced by reinforcement and by exposure in vacuum rather than air,[11] and is the dominant problem for this application. Lack of adequate data and the dependence of the total ionization on the orbit preclude a precise evaluation. It is estimated that for a 10 to 20 mil wall thickness of dielectric, years may be required to severly damage the structural properties. The most serious pehnomenon may be the increase in dielectric loss.

IV. AN "ISOTROPIC" PATTERN

An isotropic electromagnetic radiator, even without the requirement for complete coverage about a satellite whose diameter is large as compared with wavelength, is not realizable. Multiple sources of the same polarization, e.g., horns, slots or dipoles, result in a more directive pattern than is obtained from any one individual source. Linearly polarized sources that are diametrically opposite and cross-polarized (such as horns) produce nulls about the mid-section.

A polarization diversity technique is proposed to obtain "isotropic" coverage.[12] Such a scheme has been discussed before:

> The nonoriented "isotropic" satellite poses the most severe polarization problem. The only way to achieve an approximation to isotropic amplitude in the radiation is to transmit and receive different polarizations in different directions; different both in sense and eccentricity. To accommodate this at the ground terminals is not simple, so if reliable communications are desired the "isotropic" satellite is not acceptable.[13]

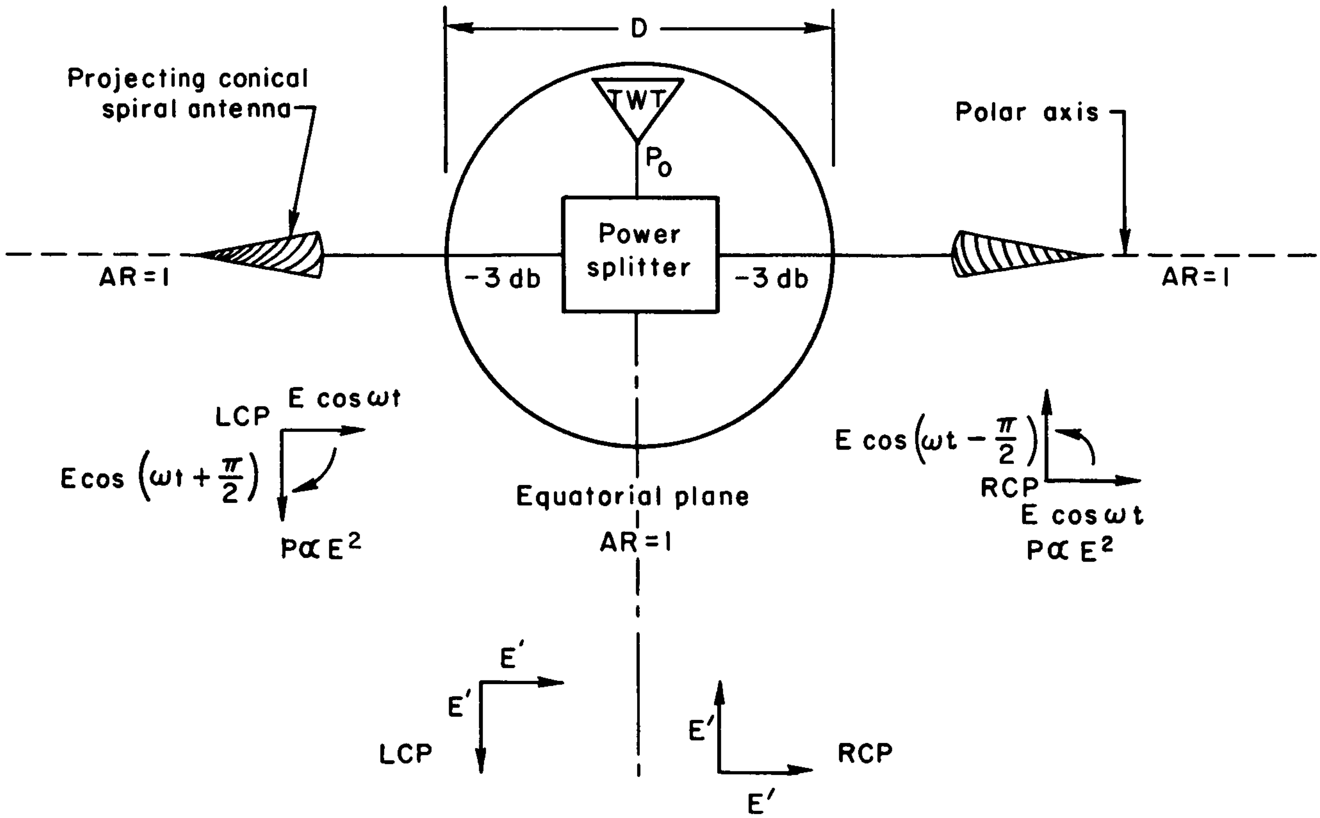
Despite this pessimism, Courier I used polarization diversity[14] reception on the down link with success. The fundamental problem is in reception at the satellite, where deep nulls in the satellite receiving pattern must be avoided, preferably without resort to the complexity of baseband combining.

Polarization diversity may be achieved by means of two extended, balanced logarithmic conical spiral antennas, diametrically opposite and circularly polarized in the opposite sense as seen by an observer in the far field. The requirement for uniform power density is that the field from a single antenna be circularly polarized everywhere, since two circularly polarized waves of opposite sense and propagating in the same direction cannot cancel regardless of how they are combined in phase.* For two fields $\overline{E}(t)$ to cancel requires that $(\overline{E}_1 + \overline{E}_2) \equiv 0$. The vectors must be equal and opposite at all times. If $\overline{E}_1$ is circularly polarized, the only possible $\overline{E}_2$ for cancellation is a vector 180 deg out of phase at every instant. This must be a circularly polarized field rotating in the same sense, but 180 deg away. Thus two antennas circularly polarized in the opposite sense cannot cancel. Since they do not cancel, there must be energy flow--thus the integral from t_1 to t_2 of $(\overline{E}_1 + \overline{E}_2)^2$ dt is not equal to zero over any interval of time.

Figure 5 shows the physical arrangement of a pair of extended conical spiral antennas on a satellite. So long as the frequency of operation maintains the excited zone of the spiral (from which radiation occurs) between the apex and mid-region, the ground plane causes only a second order effect. In addition to the cone (vertex) angle and pitch (rate of spiral angle), other variables are the top and base diameters of the truncated cone, the number of arms,(15) the relative rotation of the spirals, and the relative phase at the feed points of the two antennas. The same pair of antennas can be used for transmission and reception on different frequencies because they are quite broadband (typically the radiation patterns and input impedance are relatively constant over bandwidths of 10 to 1 or more).

The version (of spiral satellite antenna) used on Transit I,(16) is not equivalent to the one just described, because spiral antennas

*Although the author proposed this technique in late 1960, no experimental verification using two elements separated several wavelengths by a metallic structure was known to the author before the recent work of Scott, Ermatinger, Westerman and Harrington of Aeronutronics Division of Ford Motor Co.(12) William G. Scott, Supervisor of the Antenna Section, et al., have measured a minimum gain of - 3 db relative to isotropic over 100 per cent of 4π steradians for the combined pattern of two conical spiral antennas circularly polarized in the opposite sense and separated about 3λ with a metallic structure in between. (Private communication from Scott et al.)



$$\text{Resultant} \equiv 2E' \cos(\omega t + \phi)$$
$$P \propto 2(E')^2$$

For constant power density over the sphere, $2(E')^2 \equiv E^2$ or $E' \equiv \sqrt{\frac{E}{2}}$

Fig. 5—An "Isotropic" Antenna

painted on the spherical surface produce a null to the side at high frequencies. The broadband spherical satellite antenna of Ref. 16 is simply another implementation of the Turnstile, and is thus limited to roughly $D \leq \lambda/2$ satellites.

One study of an isolated conical spiral antenna indicates that beamwidths of approximately 180 to 190 deg can be obtained for a rate-of-spiral angle of 45 deg and a conical vertex angle of 20 deg.[17] Preliminary measurements in that study showed the pattern to be within approximately 6 db of being a circularly polarized isotropic source in one hemisphere. The use of two such antennas is quite different from utilizing two pairs of crossed dipoles, each pair of which produces circular polarization only when viewed normal to the plane of the dipoles and linear polarization in the plane. Two sets of crossed dipoles separated a distance D, and producing circular polarization of opposite sense as seen by an observer in the far field, would produce two essentially linearly polarized signals near the midplane, which would cancel at small angles off the midplane for $D \gg \lambda$.

The total power radiated by a single element is 3 db below P_o, the power output of the TWT. If the power from a single element were uniformly distributed over a hemisphere, the gain of the element would be + 3 db. Each circularly polarized wave may be viewed as consisting of two orthogonal linearly polarized waves, each 3 db below P_o. The power density in one of the circularly polarized waves is proportional to

$$\frac{1}{2\pi} \int_0^{2\pi} (E_\theta^{\ 2} + E_\phi^{\ 2})\, d(\omega t) = E^2$$

for $E_\theta = E\cos\omega t$ and $E_\phi = E\cos(\omega t + \pi/2) = -E\sin\omega t$, a left circular polarization (LCP = clockwise wave approaching)[18] and similarly for the right circular polarization (RCP = counterclockwise wave approaching). If an individual element has zero gain at 180 deg off axis, then the power density on axis remains proportional to E^2, the contribution of a single element. If the two circularly polarized waves are equally amplitude tapered toward the equatorial plane, and equally shifted in phase (by an angle ϕ) at the equatorial plane, then for

$$E_{\theta_1} = E'\cos(\omega t + \phi) \quad \text{and} \quad E_{\theta_2} = E'\cos(\omega t + \phi)$$

$$E_{\phi_1} = -E'\sin(\omega t + \phi) \qquad E_{\phi_2} = E'\cos(\omega t - \pi/2 + \phi) = E'\sin(\omega t + \phi)$$

the total power is proportional to

$$\frac{1}{2\pi}\int_0^{2\pi}\left(\sum E_x^2 + \sum E_y^2\right) d(\omega t) = 2E'^2$$

and thus is independent of the angle ϕ. If $E' = \frac{E}{\sqrt{2}}$, then the power density on axis and at 90 deg are equal. Thus, a 3 db decrease at broadside (the equatorial plane) in the pattern of a single element would give constant power when the two signals are summed, if the axial ratio (AR = the ratio of the two orthogonal fields of an elliptically polarized wave) remains unity. This is shown in Fig. 5.

It is thus important for this application that the axial ratio of a single element remain approximately unity from 0 to 180 deg off axis. Near the equatorial plane of the antennas, one pair of field components can cancel, but the other pair always add to produce a linearly polarized signal.

As an example of a typical overall pattern, one can analyze the combined pattern of two elements separated a distance L and each generating a cardioid pattern. The field is circularly polarized on the axis of the elements, linearly polarized in the equatorial plane, and elliptically polarized everywhere else. Since there is no null in the overall pattern, the ground receiving terminal needs only to receive circular polarization of both senses; there are available a variety of techniques, such as diversity selection or combining, baseband combining, or even tracking of the polarization. For the transmitter, the situation is more complicated.*

At the ground transmitter, the time must be predicted at which the satellite will become circularly polarized in the opposite sense to that being used. Prediction must be accurate for a time equal to the one-way propagation time and is based on data that is one propagation time old. The interval of linear polarization, as the equatorial crossing is approached, causes a 3 db loss of signal from the ground transmitter. This may be compensated for by adding 3 db of ground transmitter power, or by a 3 db increase in antenna gain. The interval of linear polarization does, however, provide a signature on the received signal at the ground receiver. From this information, the ground transmitter must determine when to switch from one polarization to the other, coincident with the crossing of the equatorial plane. Variations in the receiving pattern from satellite to satellite, differences between the transmitting and receiving patterns of a satellite, and appreciable spin rates about the two axes orthogonal to the axis connecting the satellite antennas, can greatly complicate

*No complication arises for tracking and telemetry since reception at the satellite is not involved.

the decision process. Since the ground transmitter need not follow the linear-to-circular polarization changes, but only from circular-to-circular of opposite sense, the number of switches can be kept small.

The major points to note here are that undesirable spin rates can be kept low by passive damping techniques (or by intentionally spinning the satellite about its polar axis) and that the transmitter need only use a few db more power to overcome small fluctuations in the pattern, so long as it is not cross polarized. A few db of transmitter power are more easily obtained on the ground[19] than in the satellite, and with much less expense. If the satellite is spin stabilized, then regardless of the orientation of the polar axis, generally only one switch per pass will be required. If rotation is highly damped by passive loss mechanisms, a similar result should be achievable.

If the ground transmitter changes the sense of the circular polarization transmitted by means of a gaseous switch, the transition can occur in less than 100 millimicroseconds. Another means of changing the sense of the circular polarization is to shift the phase of one of the linear orthogonal components by 180 deg (if shifted in the appropriate direction, the resultant will not go through zero). Although a ferrite phase shifter would require about 1 millisecond to perform the shift, the use of a TWT driver as a phase shifter would permit the phase shift to be carried out in less than 100 millimicroseconds. In fact since helix modulation of the TWT at 100 Mc is possible, this should permit the 180 deg phase change to occur in as little as 10 millimicroseconds; if appropriately timed, this

10 millimicroseconds should have a negligible effect at typical information rates, regardless of the type of modulation.

V. A FREQUENCY DIVERSITY TECHNIQUE

The particular implementation of frequency diversity chosen to obtain 4π steradian coverage may vary depending on the application. The one presented here is suitable for commercial systems under the typically assumed conditions of negligible interference. In this case, the satellite utilizes two orthogonal antennas, e.g., halfwave antennas, on short masts connected to dual mixers and IF receivers. A single frequency is used on the up link, and AGC levels are compared. The weaker signal channel is gated off by a Schmitt circuit (switching diversity) the normal hysteresis action of the Schmitt circuit preventing hunting. At a convenient level after the gated stages, the outputs are combined. Since only one signal is present at this point, no interference due to nulls in the combined antenna patterns can arise. The signal is then amplified and converted to a pair of sidebands in the 4 Gc range. Both sidebands are amplified in the common TWT, separated by filters and radiated by separate antennas. It is assumed that the power in the two sidebands is equal. Since the two signals are not coherent, there is no interference in the pattern. The most unfavorable satellite attitude occurs when the direction from the satellite to the ground terminal is at 45 deg angles with respect to the axes of both halfwave antennas. In this case, assuming ideal diversity reception and combining on the ground, the power relative to a single signal being amplified by the TWT and then radiated isotropically is at least -3 db; -1 db due to intermodulation products in the TWT, 3 db due to sharing the power on the two frequencies and +1 db due to the combined effects of the antenna gain (the gain of a halfwave antenna at 45 deg off axis is 4 db below the peak gain of +2 db relative to isotropic) and the combining in the receiver. There is some increase in satellite circuit complexity; assuming a constant modulation index, there is also a 50 per cent increase in the spectrum requirements. Assuming that the ground receiver uses switching diversity, i.e., it selects the stronger of the two signals, the received signal is 6 db below that received if a single signal were amplified by the TWT and radiated isotropically.

Another technique would be to radiate from only one antenna at any given time. If only one signal were amplified and then radiated via the halfwave antenna having maximum gain in the direction of the ground receiving terminal, the minimum received power would be -2 db relative to isotropic. This represents a 1 db improvement over diversity reception and combining and 4 db over switching diversity. To eliminate the need for high switching rates, all satellite rotation must be highly damped. In order that the satellite complexity not be greatly increased, the choice of antenna should be made on the ground and communicated to the satellite. Although directions for switching between the antennas could be communicated via a very narrow band command link, changing the frequency in the ground-to-satellite path to direct the energy to the preferred antenna seems preferable on the basis of reliability.* In this case, passive components such as filters

*This was suggested by E. Bedrosian of The RAND Corporation.

can perform the switching. Filter or diplexer insertion losses should be less than 1 db if the two down frequencies are adequately separated. Since the determination of the preferred antenna can be best made at the receiving terminal, this must be carried out at acquisition and communicated to the transmitter terminal. During the pass, the change in signal due to the change in inverse square spreading loss plus path loss must be separated from that due to the antenna directivity in order to determine when to switch, unless a small narrow band reference signal is transmitted on the other antenna for comparison purposes. Since two frequency bands are required to route the signal to the appropriate satellite antenna on the down link, the spectrum requirements for a constant modulation index are doubled.

VI. CONCLUSION

Of the three methods of obtaining broad angle antenna coverage from a satellite whose diameter is large as compared with wavelength described in this Memorandum, the extension of a biconical antenna on a long mast requires more weight than either the polarization diversity method or the frequency diversity techniques. For a 10 watt satellite capable of roughly 100 per cent duty operation, the estimated satellite weight of about 175 lb[10] would be increased by about 30 lb to provide the biconical antenna on the mast, two side arms for stabilization and the three motor drive mechanisms. Extension involves a one shot reliability problem, but there appears to be no long term reliability problem associated with this antenna system. Antenna coverage over 90 to 99 per cent of 4π steradians, with a gain of -1 db relative to isotropic, appears achievable with spin stabilization about the axis of the mast, and is independent of the space orientation of the spin axis over the long term.

The circular polarization diversity method represents a weight increase of only 5 lb, with a negligible effect on satellite reliability. The ground transmitter must track the polarization of the satellite and switch the sense of the circularly polarized transmitted signal as the equatorial plane of the satellite is crossed. The interval of linear polarization in the satellite pattern in the equatorial plane provides a useful signature to the pattern which indicates when to switch. Damping of all rotation of the satellite to a fraction of a revolution per pass permits arbitrary orientation and reduces the switching rate to no more than once per pass. Coverage over 4π

steradians, although of variable polarization, has been proven possible; although -3 db relative to isotropic has been achieved,[12] further improvements in the amplitude taper and in maintaining circular polarization over the 360 deg azimuthal pattern of a single element may make a higher minimum gain possible.

In addition to the 4 db loss (relative to one signal) associated with processing two signals through a common TWT, frequency diversity results in an increase in satellite complexity and in spectrum requirements. For the first frequency diversity technique, processing multiple signals through a common output amplifier or resorting to multiple output amplifiers is required. It seems preferable to reserve these for providing two-way communication via a single satellite or for easing the multiple access problem, rather than using them to solve the satellite antenna coverage problem. The second frequency diversity technique bypasses this problem. Since the improvement in gain resulting from frequency diversity antenna selection (the second frequency diversity technique) is small compared to the circular polarization diversity method, and since both provide comparable coverage to ground terminals, the choice between them depends on the importance of spectrum conservation and on the relative difficulties involved in obtaining switching information and implementing the switching (of polarization or frequency) on the up link in an operational system.

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